# VOLTAGE AND CURRENT MEASUREMENTS OF A LASER PREIONIZATION TRIGGERED HIGH VOLTAGE SWITCH

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## Abstract

Voltage and current measurements of a laser preionization triggered spark gap switch (50 kV, 18 kA, 100 nsec) reveal a voltage drop across the gap of several kilovolts during the current plateau for a variety of gas mixtures. This voltage drop is much larger than what is generally believed to exist in a spark gap switch during the conduction phase. The reasons for the large voltage drop are explained.

## Introduction

Spark gaps are commonly used devices in applications where high voltages and currents must be economically switched in short times. The holdoff voltages required for these applications range from tens of kilovolts to a few megavolts, and conduction currents range from tens of kiloamps to a few mega-amps.

It has generally been thought that the spark column voltage drop in these devises is only a few hundred volts during the conduction phase. This is correct for long duration and/or low current sparks [1]. However, for short duration, high current, single channel sparks, the results discussed in this paper demonstrate that the resistive voltage drop during the conduction phase is substantial (several kilovolts).

## Experimental Setup

The experimental system is described in detail elsewhere [2]. The apparatus consists of a 1.5 $\Omega$, 100 nsec waterline that is pulsed charged in 1.8 $\mu$sec by a two-stage Marx bank to a voltage between 40-100 kV. Attached to the waterline is a chamber that houses a laser triggered spark gap. The spark gap consists of two hemispherical copper electrodes placed 1.2 cm apart, each having a 1 mm diameter hole through their centers. The preionization laser beam (KrF, 248 nm) enters the electrode gap through the hole in the anode, is focused at a point midway between the electrodes, and passes through the hole in the cathode without striking either of the electrodes. This method of triggering produces a spark channel which is very reproducible, axisymmetric, and is accurately controlled both temporally (jitter <4 ns) and spatially (jitter <10 $\mu$m).

The low jitter and the temporal and spatial reproducibility of the spark columns obtained by use of laser preionization triggering permits the spark column to be studied with a pulsed laser interferometer. Access for optical diagnostics is provided by two sets of ports located orthogonally around the spark gap housing. The laser interferometer, also described in Reference 2, provides a measure of the diameter of the current carrying portion of the spark column with a time resolution of <5 ns. This diameter is used to calculate the inductance of the spark column in the manner described below.

A typical interferogram of the arc in a laser triggered spark gap obtained with our laser interferometer is shown in Figure 1. The outermost fringe shift is due to shockwave compression of the ambient gas. The inner fringe jump is caused by an abrupt rise in ionization of the gas. Reference 2 has a more detailed description and interpretation of the interferometer measurements.

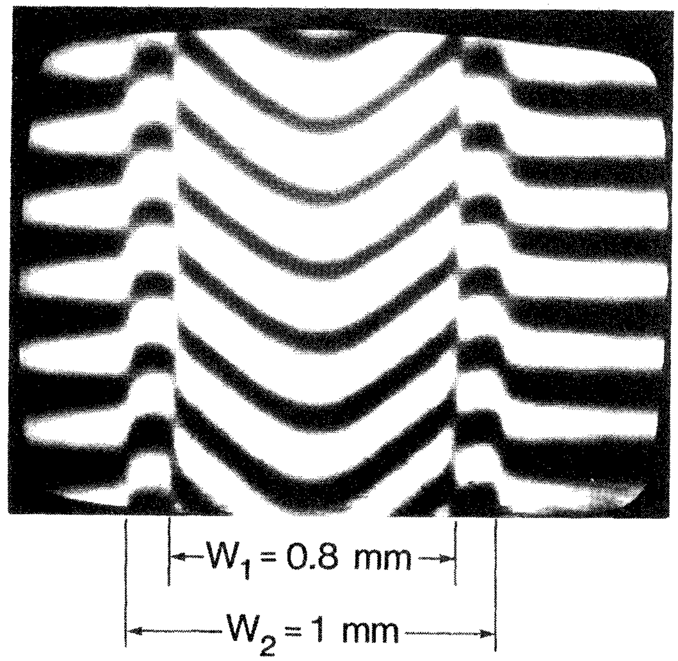


**Figure 1.** Typical interferogram of the arc in a laser preionization triggered spark gap taken 40 ns after breakdown. The gas mixture is 2 atm of $Xe/H_2$:0.01/0.99. The voltage on the waterline at the time of triggering is approximately 40 kV. The time resolution of the interferogram is <5 ns. The width $W_1$ indicates the diameter of the current carrying core of the arc. The width $W_2$ indicates the total diameter of the arc, including a high density, largely neutral shell surrounding the ionized core.

In order to determine accurately the voltage drop across the spark gap, a fast (< 1 nsec) capacitive voltage divider (CVD) probe was developed specifically for this switch device. The CVD, shown schematically in Figure 2, is only briefly described here since details of the design and construction of the device appear elsewhere [3],[4]. The CVD is annular in shape and is mounted within the spark gap chamber. The capacitors, $C_1$ and $C_2$, consist of three flat rings which are centered on the spark column axis and oriented perpendicular to the axis. $C_1$

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14. ABSTRACT
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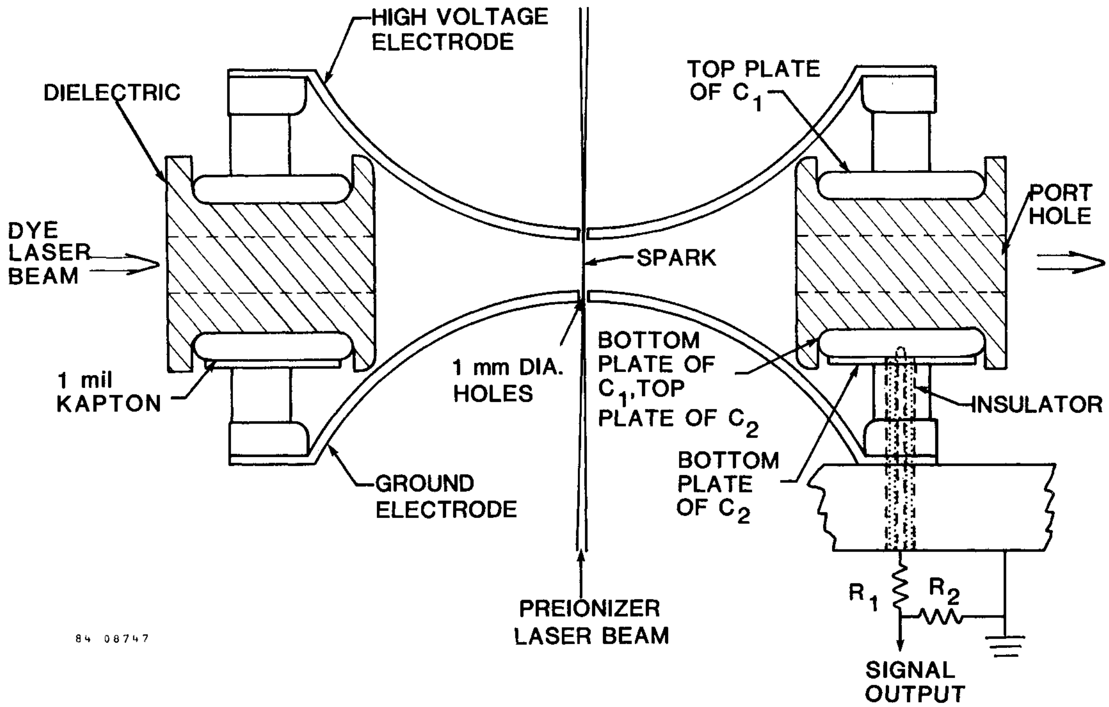


**Figure 2.** Schematic of the capacitive voltage divider (CVD) voltage probe showing the mounting configuration around the spark gap electrodes. The CVD is annular. The figure is a section taken through the center of the electrodes. The electrode separation is 1.2 cm.

corresponds to the capacitance between rings 1 and 2 while the capacitance between rings 2 and 3 corresponds to $C_2$. The solid dielectric between rings 1 and 2 is polyethylene; the dielectric between rings 2 and 3 is a single layer of 0.025 mm-thick Kapton. The upper and lower plates of capacitors $C_1$ and $C_2$ are directly connected to the anode and cathode electrodes, respectively. This geometry minimizes the inductance of the CVD and minimizes the inductive component of the voltage measured by the CVD. The rise time of the probe is estimated to be less than 1 ns.

The values of $C_1$, $C_2$, $R_1$, and $R_2$ were chosen to ensure that the error in the voltage measurement due to voltage decay across $C_2$ during the current pulse (≈100 ns) is less than 1%. However, the time required to charge the waterline (1.8 µs) is not short compared to the RC time constant for the decay of the voltage on $C_2$ (RC = 9.8 µs). Therefore, the voltage indicated by the probe, $V_o$, at the time of triggering is less than the charging voltage on the waterline, $V_\ell$. The values of capacitors $C_1$ and $C_2$ were determined experimentally (see below) and the time rate of change of voltage on the waterline during charging is accurately known by experimental measurements; therefore, this effect can be corrected for by analysis of the equivalent circuit for the CVD [3],[4],

$$V_o(t) = V_o(0)\exp(-t/RC) + \frac{R_2C_1}{RC}\exp(-t/RC) \cdot \int_0^t \frac{dV_\ell(t')}{dt'}\exp(t'/RC)dt'. \qquad [1]$$

where $C = C_1 + C_2$, and $R = R_1 + R_2$. For our conditions, the voltage indicated by the CVD at the time of laser triggering of the spark gap is $0.91 \cdot V_\ell$. During the current pulse, the change in voltage from the initial value as indicated by the probe is used without further correction.

For $V_o(t)$, as calculated from Eq. 1, to be accurate the values of $R_1$, $R_2$, $C_1$, and $C_2$ must be precisely known. The resistors $R_1$ and $R_2$ are discrete components, enabling their values to be accurately measured using conventional resistance meters. The capacitance $C_2$ was measured *in situ* using a vector impedance bridge, yielding a value of 5.0 nF. Due to access limitations, a direct measurement of $C_1$ cannot be made. The capacitance of $C_1$ was obtained by measuring the total attenuation of the probe for a known voltage input; and using the known values of $R_1$, $R_2$, and $C_2$ to calculate $C_1$ from Eq. 1. This was done using the voltage across the spark gap during the charging cycle of the pulse forming line (PFL). During the slow (1.8 µs) pulse charging of the PFL, the spark gap voltage can be reliably measured using a resistive divider probe thereby providing a reference value. Using this method, we obtained a value of 11.5 pF for $C_1$.

As an additional check of the capacitance values, the voltage decay time constant of the output of CVD was measured. Since $R_1$ and $R_2$ are accurately known, and the attenuation factor is known, the values of $C_1$ and $C_2$ can be obtained from Eq. 1. Using this method, $C_1$ and $C_2$ were found to be 10.66 pF and

4.35 nF respectively. Since the duration of the current pulse (≈100 ns) is small compared to the RC time constant of the CVD (9.8 μs), Eq. 1 can be approximated as $V_o(t) = (R_2C_1/RC) \cdot V_s(t)$. The uncertainty in our voltage measurements is therefore the uncertainty in the derived attenuation factor $C_1/C$. From our two determinations of this ratio, the uncertainty in our voltage measurements is ±3.2%.

The current through the spark column is measured with a current viewing resistor (CVR). The CVR consists of an Inconel foil surrounding the spark gap chamber which completes the current return path between the switch and load resistor, and the waterline.

## Results and Analysis

Typical voltage and current waveforms of the spark column are given in Figure 3. The gas mixture in the spark chamber is $SF_6$ at 0.4 atm. As can be seen, the current reaches a plateau value of approximately 17-18 kA after 60 nsec into the spark breakdown. The voltage during this current plateau is 2-3 kV.

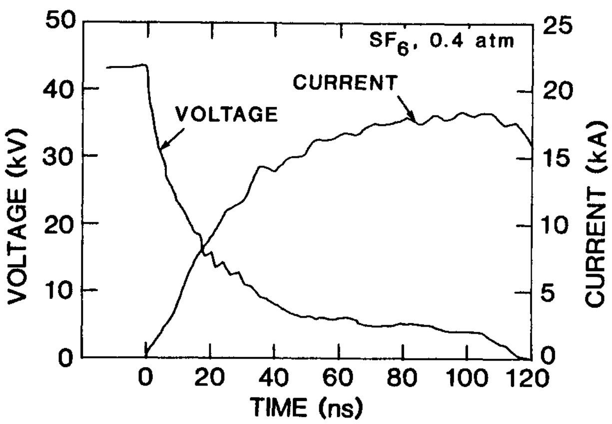


**Figure 3.** Typical voltage and current traces taken with the current viewing resistor and capacitive voltage divider (CVD). The gas is 0.4 atm of $SF_6$. The voltage scale has been corrected for droop in the CVD that occurs during the 1.8 μs charging time.

With this voltage and current data, the time dependent resistance of the arc in the spark gap, $R_s(t)$, can be determined by calculating $V_r(t)/I(t)$, where $V_r(t)$ is the resistive voltage drop across the arc and $I(t)$ is the total current. However, the voltage measured by the CVD is

$$V_o(t) = I(t) \cdot R_s(t) + [L_s(t) + L_f] \cdot \frac{dI(t)}{dt} + I(t) \cdot \frac{dL_s(t)}{dt} \qquad [2]$$

where $L_s(t)$ is the time varying inductance of the spark column and $L_f$ is a constant inductance value attributable to the geometry of the electrodes (≈5 nH). For our conditions, the last term in Equation 2 is small and can be neglected. To obtain $R_s(t)$ from Equation 2, the measured voltage and current waveforms (as they appear in Figure 3) are digitized and entered as inputs to a computer program. In the program, the current waveform is numerically differentiated to provide $dI(t)/dt$. The last remaining quantity required to solve for $R_s(t)$ is the spark channel inductance $L_s(t)$. This value is obtained from the time history of the spark channel radius as measured from laser interferograms taken coincidently with the voltage and current measurements. Assuming current flows uniformly through the spark column, the value of $L_s(t)$ is given approximately by

$$L_s(t) \cong \ell \cdot \frac{\mu_o}{2\pi} \ln\left[\frac{r_c}{r_s(t)}\right] \qquad [3]$$

where $\ell$ is the length of the spark column, $r_c$ is the radius of the current return path (≈14 cm), and $r_s(t)$ is the radius of the spark channel obtained from the interferograms. With this value of $L_s(t)$, it is possible to solve for the spark channel resistance $R_s(t)$ from Equation 2.

The high voltage drop during the current plateau implies that the resistance of the spark column during that time must be also be high. Calculating $R_s(t)$ from the V-I data for a number of different gas mixtures confirms this fact. The results are shown in Figure 4 for four gas mixtures. We see that the $SF_6$ mixture has a plateau resistance of ≈0.3 Ω; whereas the $Xe/H_2$:0.01/0.99 mixture, which has a smaller average molecular weight, has a plateau resistance of ≈0.1 Ω.

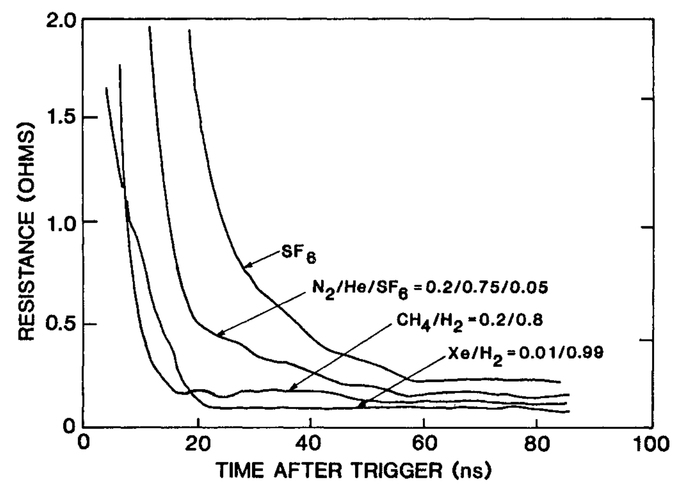


**Figure 4.** Calculated arc resistance for various gas mixtures. Breakdown voltage is ≈40 kV. Note, the data shown are at a different percentage of self-break for each of the gas mixtures because of their different voltage stand-off capabilities.

## Discussion

The large voltage drops measured during this experiment are not unreasonable; one should keep in mind that the conditions of our experimental study are in a parameter space not previously addressed in detail. The duration of our current pulse (≈100 ns) is shorter, and the current density in our spark column (≈2 MA/cm$^2$) is higher than the typical self-breaking spark columns previously studied [1]. Furthermore, in the earlier studies it was not known

the number of channels that were formed during the self-breakdown process (self-break measurements on our device indicate that the switch will often breakdown through multiple channels). In our experiment, laser triggering assured that only one channel was formed during breakdown. However, some limited comparison can be made to the earlier work by examining the properties of those spark columns during the first hundred nanoseconds of their current pulses.

Early during the conduction phase of a spark gap, whether it is laser preionization triggered, electrically triggered, or self-breaking, the resistance of the arc between the spark gap electrodes is large compared to the load. During the first tens to hundreds of nanoseconds after triggering (or self-break), the plasma arc expands from an initial diameter of ≈50 μm [2] to a diameter greater than a millimeter. As the arc expands and increases its cross-sectional area, the resistance of the arc decreases proportionally. The time required to reduce the resistance of the arc from an initially large value (many tens of ohms) to a resistance small compared to the load ($\leqslant 0.1\ \Omega$) is, therefore, dictated by the hydrodynamic time scale; that is, the time required for the arc to hydrodynamically expand to sufficiently large radius [2],[5]-[7]. If the duration of the current pulse delivered to the load is comparable to the time required for the arc to expand, resistive losses in the switch will be non-negligible.

We believe the high voltage drop and high plateau resistance which exists for our particular switch conditions can be understood as follows. As the arc expands, the resistance of the arc decreases simply as a result of the increase in the cross-sectional area of the arc. But as the cross-sectional area increases, the temperature of the arc decreases as a result of a lower volumetric heating rate. Therefore, the resistance of the arc is a convolution of these two opposing effects.

The average electrical conductivity of the arc may, in fact, decrease simultaneously to the total resistance decreasing provided that the area of the arc increases at a sufficiently high rate. The result of these opposing effects is that the resistance of the arc decreases proportionally to $A^{-2/5}$ instead of $A^{-1}$, where A is the cross-sectional area of the arc [8]. A more detailed discussion of the arc resistance can be found in Reference [8].

Hence, for our single channel, laser triggered spark, the growth of the cross-sectional area of the column is controlled by the hydrodynamics of the gas expansion. The net effect is that the average electrical conductivity of our arcs during the conduction phase is low enough to create an appreciable voltage drop across the spark. Further evidence that the resistivity of the spark is a function of the gas hydrodynamics can be seen in Figure 4 which demonstrates that the plateau resistance changes depending on the average molecular weight of the gas mixture (we should note however that the data shown in Figure 4 are not taken at the same percentage of self-break for each of the gas mixtures).

## Conclusion

Measurements of a laser preionization triggered spark gap indicate that the voltage drop across the arc operating through a single channel is in excess of 2 kV for current pulses of 17-18 kA. It is found that the arc resistance during the 100 ns current pulse falls to a plateau value that remains in excess of $0.1\ \Omega$ for a variety of gas mixtures. The plateau value of the resistance decreases for decreasing average molecular weight of the gas mixture. This dependence on molecular weight results from the fact that the arc expands primarily by hydrodynamic motion of the hot ionized core; lighter gases expand at a faster rate and, therefore, have a larger cross-sectional area at a given time after triggering.


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